PROGRAMMED INSPECTION MACHINES

Robert Lee
Brown and Sharpe Manufacturing Co.
North Kingstown, Rhode Island

Bob Lee from Brown and Sharp will be talking to us about program inspection machines. Bob asked me to come and talk to you about the latest technology in measuring all these creations we are developing. What is happening in the, the gas turbine industry is that the components are getting tolerance wise tighter and tighter all the time the manufactures tolerances are going down below the thousandth (of inch) range and getting in the five tenths range very rapidly. Then engineering people who design these machines are also looking for a lot of data coming back to them on the R & D level to see if the part or component is working properly; where the wear is going on etc, etc. So this is putting a lot of pressure on the gauge manufacturers; e.g., I was on the phone with Pratt & Whitney this morning and NASA is putting a tremendous amount of pressure as well other people, on people to go back to the old ten to one rule that somehow got lost and left that behind a few years ago. The old ten to one rule is that the gauge has to be ten times better than the tolerance that your checking and somewhere we lost that; also the data density is changing especially when we get into air foils and seals etc, where I'm looking for a particular form or shape. The customers are asking us to produce huge amounts of inspection data in very, very short periods of time. So if I have root form on a turning blade or something of this nature and they want to be able to take five or six thousand data points that defines that object three dimensionally in under a minute. Those are the types of constraints that we are working under what I'd like to do today is just show you some typical equipment which we manufacture and how it relates to the type of outputs we're seeing. One of the other areas of immediate interest is the area of three dimensional models, solid models. Now how do I take that and transfer that to the shop floor? I have an inspector out there he has no blueprints; all he has is a soft model - and that's another whole set of problems which we are dealing with. There are now software packages we are putting together and third parties are putting together, which will allow you to do that take the solid model measure this object and then do a three dimensional best fit back to the CAD system to see if this is an acceptable product. In the old days what you had in many instances was a sectioned model data or form of the component; in the case of the turbine blade it would probably be a root form and section of the root, the pressure face. The root form today what the customer is saying is that is not enough data, it is also needed here, here, here, and here. So now I might have six data points that have to fit into a three dimensional envelope. In order to do that you have to collect an awful lot of data and then do what we call 3D shape fit 3D best shape fit. Those are the types of issues we face. What I'm going to show you first is some of the typical equipment how it's used where it used and then I'll get into the outputs of that equipment this is a very simple cord and measure machine multi axes cord and measure machine it rides upon air bearings; we're using it in conjunction with a PC here and a simple printer and this is typically used by the aerospace industry for checking small components they could be blades, they could be seals, they could be anything else you wanted to check. We are looking at an accuracy range here in the neighborhood of six to eight microns, that type of accuracy for this type of machine. We use what they call a trigger probe a sensor that when you touch the object it records the position of the machine and then feeds that information to the computer; this is again a typical machine that's used in manufacturing. The next machine we have is used again it's a small horizontal machine it's design for very high speed going in again and touching the object and grabbing the whole series of points. This is used in the aircraft industry - very extensively by Pratt-Whitney and General Electric for taking a blade on the shop floor, doing a whole bunch of measurement points on it and seeing if the blade form is relating correctly to the root form. So again this is another type - it's a shop floor type machine. There's migration of the equipment to the shop floor and the goal is to be able to take your product machine it, inspect it, if it is marginal do a trend analysis and then correct the machine tool. And this is done at high speeds in the sense that the part will be inspected here at about thirty to forty seconds and that information feedback to the controller. Based on the trend analysis you actually control the machine tool. So this is very important in the case of compressor blades where you have high volume of parts coming through all the time.

Now, we get into a different type machine. Although it looks the same, what we are migrating to in the industry is high speed scanning; so instead of coming in and touching a whole series of times, I now have a full contact probe with 3D sensor capability so I can now pick up an object and say, start here and end here; and it will scan it and collect up to a thousand points per second as I'm traveling. Again this particular machine we're looking at we're talking in the accuracy range of about five microns, scanning contours at that rate; so these could be lip seals, they could blades, they could be anything we could travel and gauge up to four inches per second. So its very high speed, lots of data collection and again we have several different layers or types of software. Some are very simple geometric software others are extraordinary complex 3D best fit software which we would use for blades, gears, things of this nature. So for this type of machine, we're again getting into the high speed scanning of objects collecting lots of data on blade forms, or seal forms or whatever and to a fairly high degree of accuracy; now we get into the Rolls-Royce here. We get into the products manufactured in Germany (DER, Leitz). And in the space arena, I was on the phone this morning to the space shuttle pump group as an example, perfect example. Their measured blade root form is now being reduced to a total tolerance of five tenths of the whole blade root form which means that with their requirements the gage has to be able to produce a six sigma fifty millionths accuracy and that's what this machine will produce; this machine is accurate to one micron. It has high speed scanning capability. We can scan at rate of two inches per second and collect a thousand data points at that rate to an accuracy of one micron and repeatability of a half of micron. The test we were doing the other day for UTC, we were repeating in the range of five to six millionths of an inch on a piece of equipment like this at high speed scanning. Now five years ago, even just five years ago we take this machine and go to company and say this is what we'll do to your product for four million dollars they'd throw you out the door. Today their buying them left and right; it's just amazing they are realizing they have to have the accuracy - they have to have the technology to guarantee that product. We get into liability, we get into maintenance and serviceability of the engine and performance of the engine is getting tougher and tougher and tougher all the time. To give you an example, the previous gauge which did the scanning to five microns level, we are supplying now. We're talking to people supplying nozzles. Up to right now the nozzle area gauging is being done to an accuracy of five to ten percent ; that system will reduce it to one tenth of one percent. So now we can correlate the EGT temperatures from the engine much more accurately to the nozzle area. So for the technology related to jet engines or gas turbines, these machines are going in left and right and at this particular accuracy I am amazed at the companies buying two, three, four a whack. With this type of accuracy requirements so in this (next panel) what we were looking at is the leading/trailing edge dove tail form; what the gauge produces is a output of this type here so it allows the person to look this is deviation, black outline is nominal, the red is deviation - so it allows them look out at a half micron accuracy of what that pressure face really looks like and we're doing it at two levels so we can also tell - do we have a taper up problem? do we have twist problem? during the manufacturing, just what the problem is; so this allows me look at the these tolerances at just tremendous detail. What's also happening is, is as the requirements become tighter from the manufacturing the same requirements are being put on the overhaul people and that is going to get tougher and tougher and tougher because of the close tolerance of the parts work to maintain engine performance as you get up over thirty to one pressure ratio, the blade shape the form, the roots, all this are critical to performance. So when I bring it back to original engine performance I have to look at all these things very, very closely in the case of overhaul I'm looking for trends, e.g., wear, fretting, in these pressure face areas. So in order to look at them on almost a microscopic level - this type of equipment that is being used. The next situation(next panel) which is very difficult to evaluate again is filleting profile; again this is all blade stuff because we're running a blade seminar next week (Brown&Sharpe Jet Engine Symposium - October 1996) , In the old days when I wanted to measure this width 0.5 inches across here I would put a set of pins on there or hold them somehow and then measure with a micrometer recorder. Today that's all mathematically calculated for you and also shows you the deviation and the profile. What we have here (next panel) is the nominal line coming down through; what I have on top of that is the tolerance band and then red whiskers as we call them is deviation from that, that entire measurement process takes about forty seconds on the equipment with an accuracy of half a micron - so that's where the technology is going. This equipment is being put into temperature controlled cells; it is being put right on the manufacturing floor and the person takes the part out of the grinder puts it into this four million dollar gauge pushes the button it inspects it. The machine analyzes it gives them a go /no-go situation, which I'll show you later, then if, and equally important, if it's a no-go, how do I analyze what the problem? Is it a free form shape or some kind of radius shape? What this does is show very clearly to the foreman or the manufacturing engineer or whoever is involved with it, where the problem is instead of just a bunch of numbers in my hand or head. This is all migrating right to the shop floor, this is another one, I think this is analysis part I not sure, where we have multiple pin diameter is across here and the computer is calculating all that information and so down here he's got the nominal actual deviation on that particular part very quickly and then he can take that information and if its okay then just go to the next part. In this case here (next panel) we're looking at the shroud form of the turbine blade and it could be the seals also on the shroud you could be looking at, the problem with this, especially in the repair business, is with the shroud form the Z-form as we call it, a measurement onto itself is one item but then also related to the filleting, so for the repair business what I want to be able to do is to isolate whether the form is out of shape or whether the I have a twist in the blade. That's the problem and it effects the cost of repair dramatically; if I've got to go back and regrind this I've got to build it all up and regrind it. You're probably talking ten times the cost to do that versus having just to go back and reestablish the twist in the blade. So this allows us to very quickly do an inspection on the Z-form to see whether it's independent of everything else on the blade and then later on go back and calculate the twist and see if we can just repair that. Again so I isolate the problem; in the old days you used fixture gauging which is rather benign, doesn't tell you to much on the analysis side, it just says it's no good. And it doesn't tell you how to repair it so you're relying on somebody else to do that; and there's a big push in the industry for more analytical information of this type. Here's a typical blade cross section (next panel) and each one of these little whiskers (red) is a data point measured on one of the machines; and again the computer has established a center of the blade it's also calculated a thickness through the blade and has told us what kind of profile deviation we have , at a point of maximum thickness. So that's a typical blade cross section. Looks like a compressor blade. Now we get into a turbine blade (next panel). What they've done is analyzed it several different ways and again this is subject to the shop and their whim on how they want to do it and how engineering wants them to do it, the data points are here and here on this left side the - gg side - and the right hand side we've established the data point equals zero here and here (green circles) and this is based on what the manufacturers requirements are and how they shape it. Again we're doing 2D and 3D shape fitting of those forms, into the nominal profile as you see it here; so depending on what this is designed to show is depending on how you establish your datams whether this part is good or bad. In this case here it's bad over here (see red whiskers) here it's good, so the individual manufacturers look at this type of data very, very carefully. This is another way of an output of a blade (next panel) and in this case here we're computing the twist (left hand side). Most are set up for individual customers the way they like to see the data output; in this case here we've computed a twist of a hundred seventy nine degrees ; the straightness we're looking at the tilt of the blade and several other features around the blade profile. I think this is KLM blade. This is a typical output that you might have that an inspector might see (next panel) either on an overhaul shop or an production floor and he's looking at all these leading edge thickness etc, different dimensions max thickness, cord CC contour, CB contour , twist (mins) and the various datams etc. This is the output that the manufacturing person gets, numerical data and then that is tied into the graphic system to let him look at it graphically. It's tough to decide what's going on in there with just a bunch of numbers so that's when you go back into the graphics system and you start looking at what the pictures are doing; so the requirements as to what you're designing are the tighter, and tighter tolerances. The next phase is no blueprints, all solid models, solid models are down it's from the CAD system. We are developing software that will be able to go on the CAD system and say give me a slice across here and develop an actual inspection program which drives my inspection machine. The designer will pick, at his work station, how he wants his part to be inspected and he will generate that program right at the work station; and that's at the next phase of what is going on right now in the industry.

Brown&Sharpe

CMM Probing Systems

An Overview of Probing Technology in Common Use Today

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3 Basic Classes of Probes

- **Switching Probes**
- **Non-Contact Probes**
  - **Laser Triangulation**
  - Capacitance
  - Others
    - Video
    - Stuctured Light
- **3D Analog Scanning Probes**

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Switching Probes

- Based on Kinematic Mount
  - Cone-V-Flat
  - 3 Spheres/6 Cylinders
- Kinematic Joint Functions as both Reference and Switch
- Lightweight

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Dual Event Switching Probes

- Use some form of signal to register contact with part
  - Strain Gage (TP7/TP200)
  - Acoustic (Piezo) (SIRIO/TP12)
- Use Kinematic "Unseat" as confirmation of first event and to provide overtravel

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Simplicity

- Low Weight allows extension and Re-orientation (PH9/10/10MQ)
- Reorientation permits simple, automatic calibration routines
- Easy to set up and use.
- Most common type of probe in use today.

Non-Contact Probes based on Laser Triangulation

- Point Trangulation Probes
- Circular Triangulation - Wolf & Beck
- “Stripe Triangulation”

Point Triangulation

- Views reflection of spot from a known angle - computes the standoff to reference point.
- Disadvantage - can be blocked by other features on part surface.(or fixturing)
- Multiple eye sensors increase ability to avoid being blocked.

Circular Triangular

- Uses a circular receiver to detect a “cone” of laser light reflected from the part surface.
- Cone angle is known - Diameter of received circle is used to calculate “standoff”
- Less sensitive to changes in angle of incidence - resists blocking of beam.

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Scanning with Laser Probes

- Both these types of Laser Probes can scan
- Both tend to be medium weight
- Both can be re-oriented for easy calibration and access to part features.
- Scan data can be "Section Based" - matching dimensioning concepts
- Data is already at part surface - no radius correction necessary.
- Low risk of collision - due to standoff

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Scanning Concepts

- Defined Path - The nominal (theoretical) shape of the part is used to control the motion of the CMM. Speeds are typically higher (25 to 150 mm/sec). The probe is used to measure the difference between the nominal and actual part profile.

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Scanning Concepts

- Undefined Path - Information from probe is fed back into motion control loop so CMM can perform "Terrain Following" on an unknown surface. Speeds are generally from 5 to 50 mm/sec.

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"Stripe Triangulation"

- Stripe is generated by moving optical components.
- Measurement occurs as with point sensors.
- A "swath" of data can be acquired in one pass. Excellent Thruput.
- However it is not "Section Based" and must be "reduced" to match Section data.

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Analog Contact (Scanning) Probes

- Miniature CMM
- 3 Mutually Perpendicular Axes
- Continuous Measurement Capability
- Examples include:
  - Leitz PMM
  - Leitz TRAX/miniTRAX
  - Renishaw SP600

Precision

- Calibration corrects bending of probe with 3D matrix.
- "Averaging" effect on single points gives best repeatability
- Sub-micron Repeatability in single point mode.

Thruput - Scanning

- Contact Analog Probes provide thruput via Scanning.
- Both modes are supported (Undefined and Defined)
- Data rates of ~200 pts/sec. (high speed link between Controller and Computer)
- Accuracies under 5 microns even while scanning.

Two Probe Assy. Strategies

- Fixed Probe Heads support large, long and complex (if necessary) Probe Assemblies.
- Smaller Probe Head (SP600) provides access by re-orientation - not appropriate for probes longer than 200 mm.

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Probe Comparisons

	TTP	Laser	Analog
Pts/sec	1.2	200	200
Pts/sec (future)	1.5	1000	1000
Repeat.	2uM	~10uM	<1uM
Cost	2K$	15K$	10K$-20K$

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Summary

- Switching Probes:
  - simple - point to point only - articulated w/PH9-10
- Laser Probes:
  - Scanning - single eye - multi eye - circular -
  - standoff avoids collisions - less precise (~10 uM)
- Analog Probes:
  - Scanning - higher precision - Best Combination of precision and thruput

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Special Considerations

- Probe Compensation
- Machine Positioning Accuracy
- Variation in Airfoil Location
- Airfoil Feature Calculation

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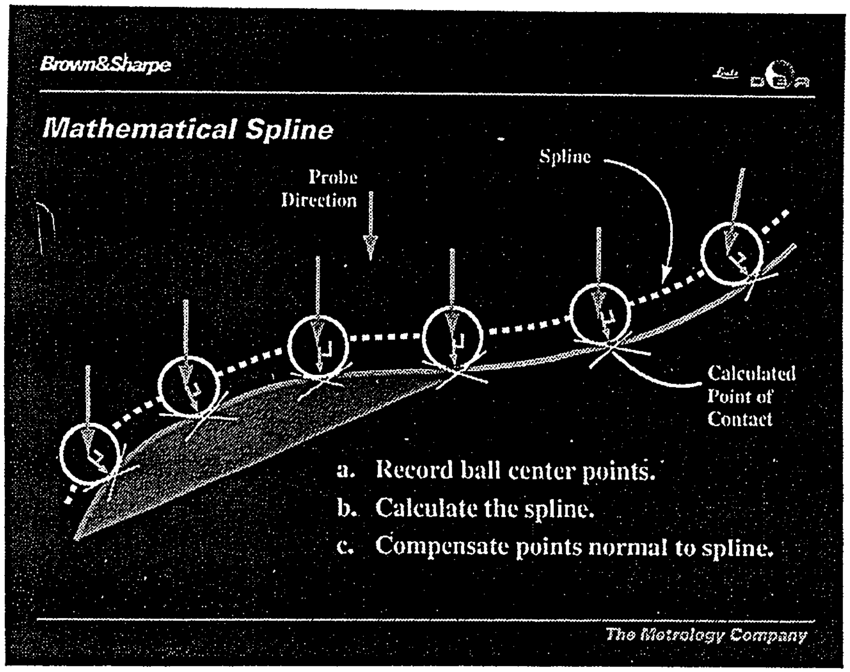

Brown&Sharpe
Mathematical Spline
Probe Direction
Spline
Calculated Point of Contact
a. Record ball center points.
b. Calculate the spline.
c. Compensate points normal to spline.
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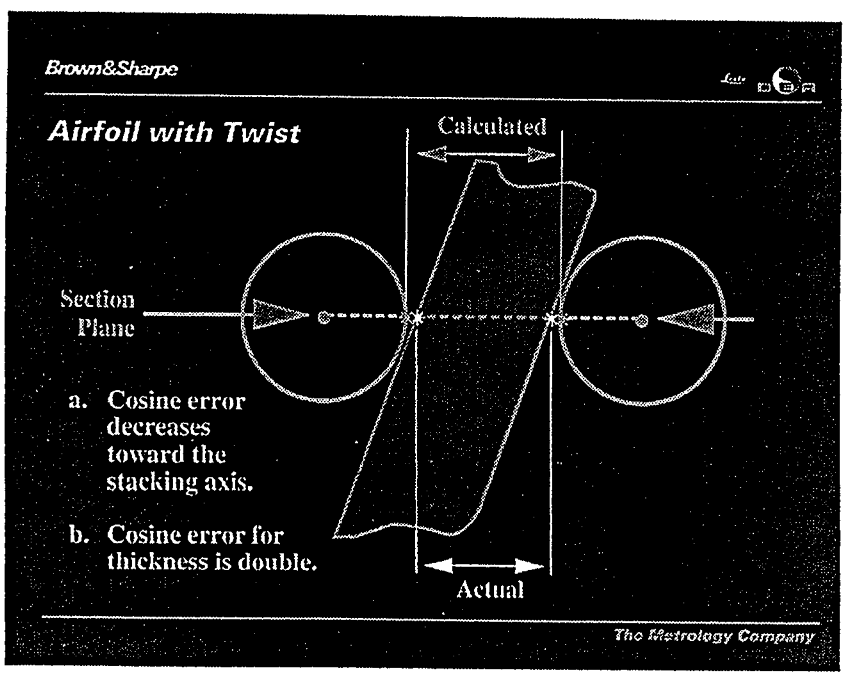
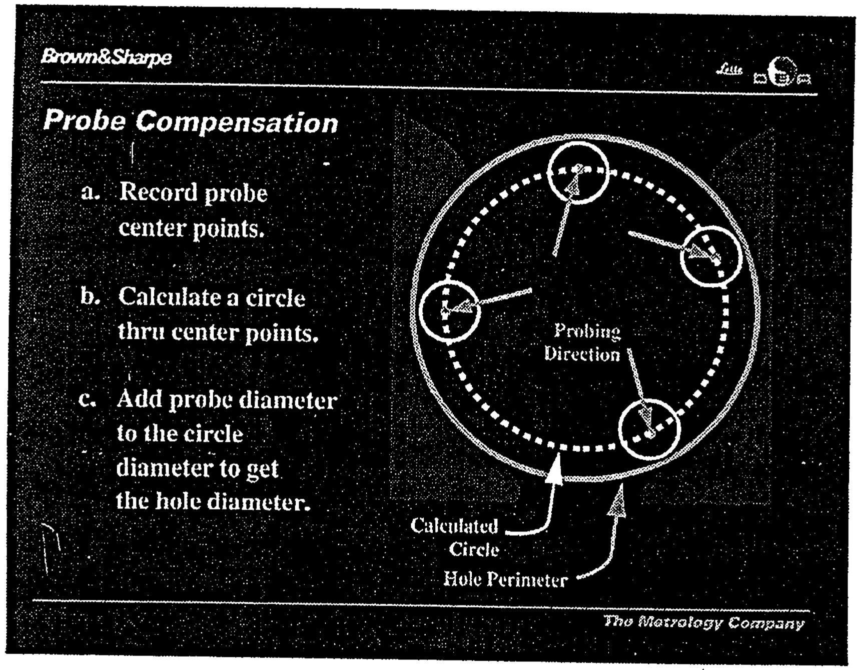


Brown&Sharpe
Airfoil with Twist
Calculated
Section Plane
a. Cosine error decreases toward the stacking axis.
b. Cosine error for thickness is double.
Actual
The Metrology Company



Brown&Sharpe
Probe Compensation
a. Record probe center points.
b. Calculate a circle thru center points.
c. Add probe diameter to the circle diameter to get the hole diameter.
Probing Direction
Calculated Circle
Hole Perimeter
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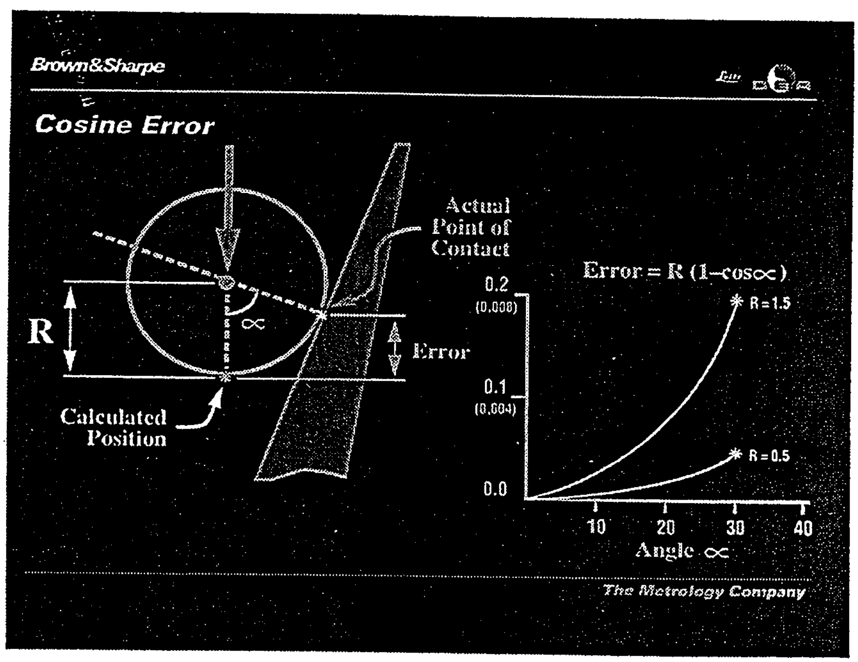

Brown&Sharpe
Cosine Error
Actual Point of Contact
R
Error
Calculated Position
Error = R (1−cos∝)
0.2
(0.008)
0.1
(0.004)
0.0
R=1.5
R=0.5
10
20
30
40
Angle ∝
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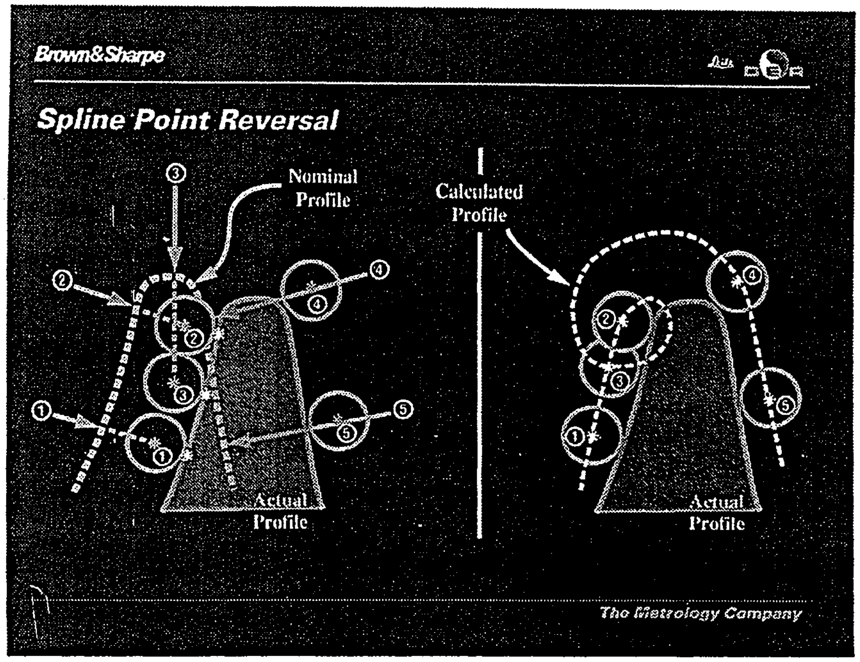
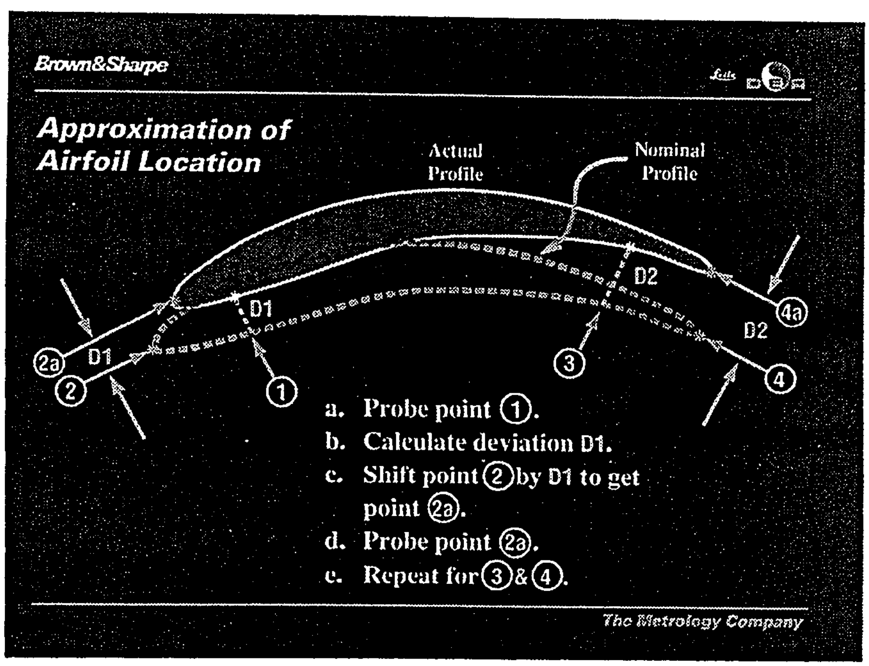

Brown&Sharpe
Spline Point Reversal
Nominal Profile
Calculated Profile
Actual Profile
Actual Profile
The Metrology Company


Brown&Sharpe
Approximation of Airfoil Location
Actual Profile
Nominal Profile
D1
D1
D2
D2
a. Probe point 1.
b. Calculate deviation D1.
c. Shift point 2 by D1 to get point 2a.
d. Probe point 2a.
e. Repeat for 3 & 4.
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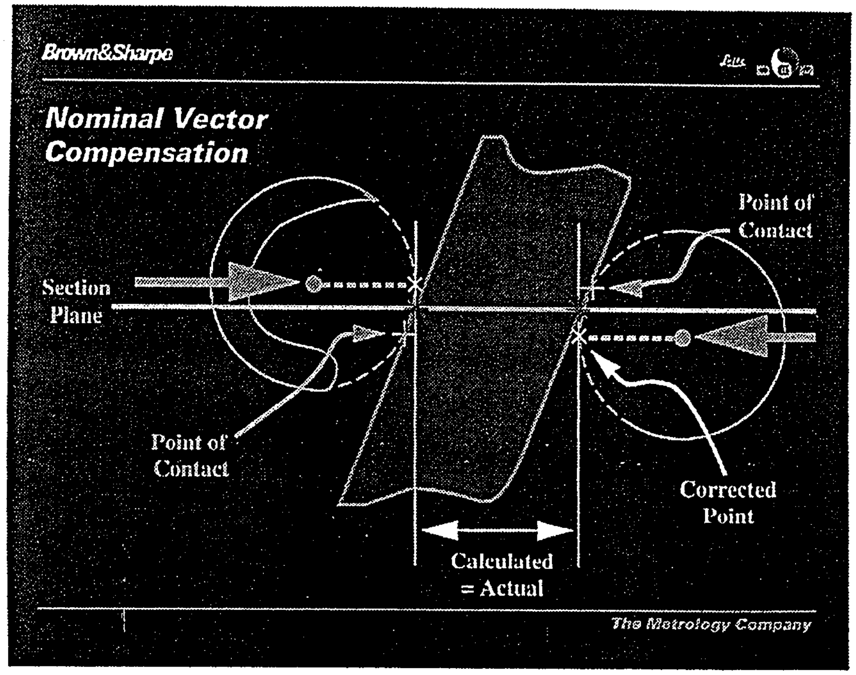
Brown&Sharpe
Nominal Vector Compensation
Point of Contact
Section Plane
Point of Contact
Corrected Point
Calculated = Actual
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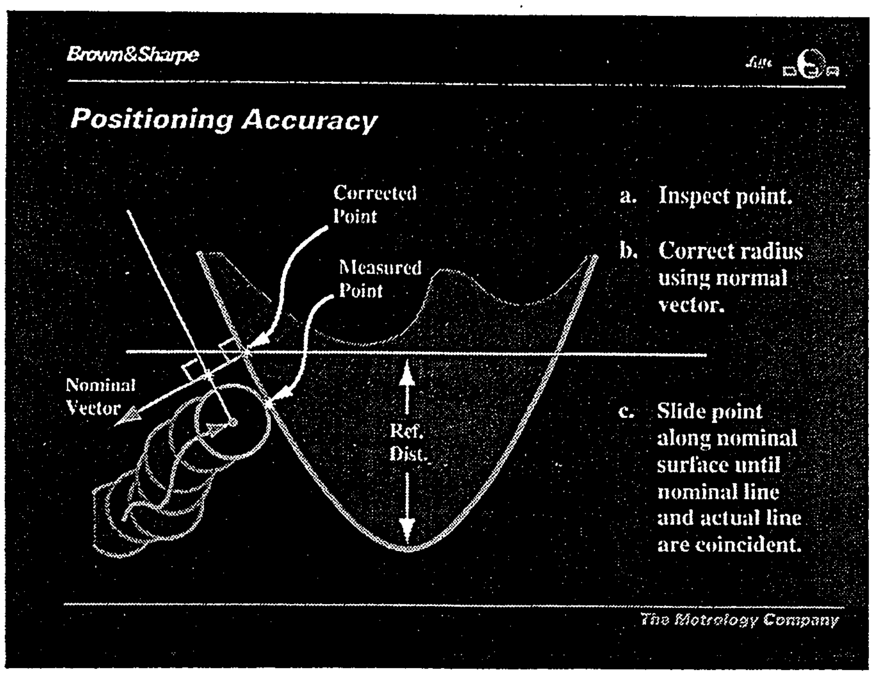
Brown&Sharpe
Positioning Accuracy
Corrected Point
Measured Point
Nominal Vector
Ref. Dist.
a. Inspect point.
b. Correct radius using normal vector.
c. Slide point along nominal surface until nominal line and actual line are coincident.
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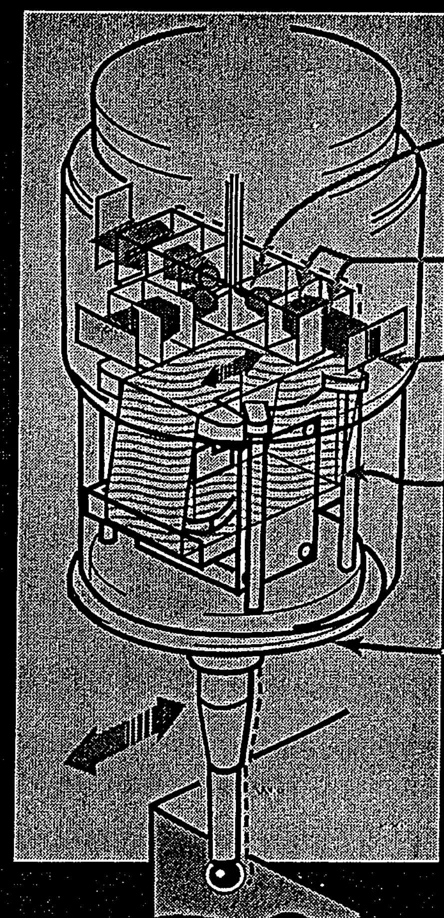
Brown&Sharpe

Inside the Renishaw® SP600



Light Sources (LED)

Light Aperatures

Detecting Array

Parallelogram Spring Motion Mechanisms

Stylus Module with Magnetic Coupling

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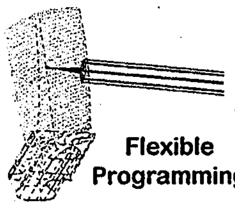
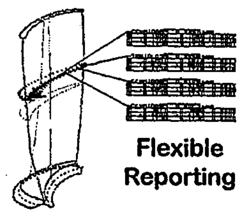
Origin International Inc.

Flexible Measurement

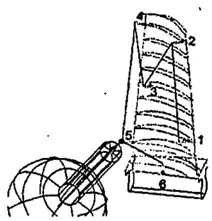


Flexible Programming

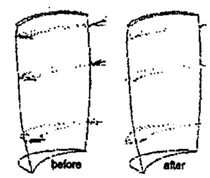
Measuring the compound curvature shapes created within modern 3D CAD systems brings new challenges to turbo industry manufacturers



Flexible Reporting



Flexible Datuming



Flexible Analysis

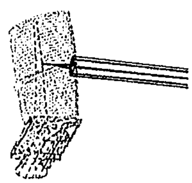
Origin International Inc.

3D vs 2D techniques

- **2D drawings required 2D techniques**
  - **feature to feature relationships**
  - **feature location**
  - **feature form**
- **complex 3D CAD designs**
  - **new problems**
  - **new opportunities**
  - **new techniques**

Origin International Inc.

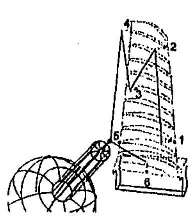
Flexible inspection programs



- quickly edit CMM programs
  - engineering changes
  - material offset
  - stock allowance
  - customer requirements
- quickly modify CMM programs
  - more variability - more information
  - less variability - less information
- quickly output CMM programs
  - DMIS and Native languages
  - multiple metrology packages & versions

Origin International Inc.

Flexible fixturing (software fixturing)



- fast fixture-free alignments of complex surfaced components
- can align without prismatic features
- handles overspecified alignments by balancing errors
- a way to reduce costly fixtures
- better probe access
- easier to program
- fewer set-ups
- better repeatability

RESULTS FOR SECTION : AA

PROFILE TOLERANCE 0.005, ERROR MAG x 5

MEASUREMENT UNITS : ENGLISH (error / 1000)

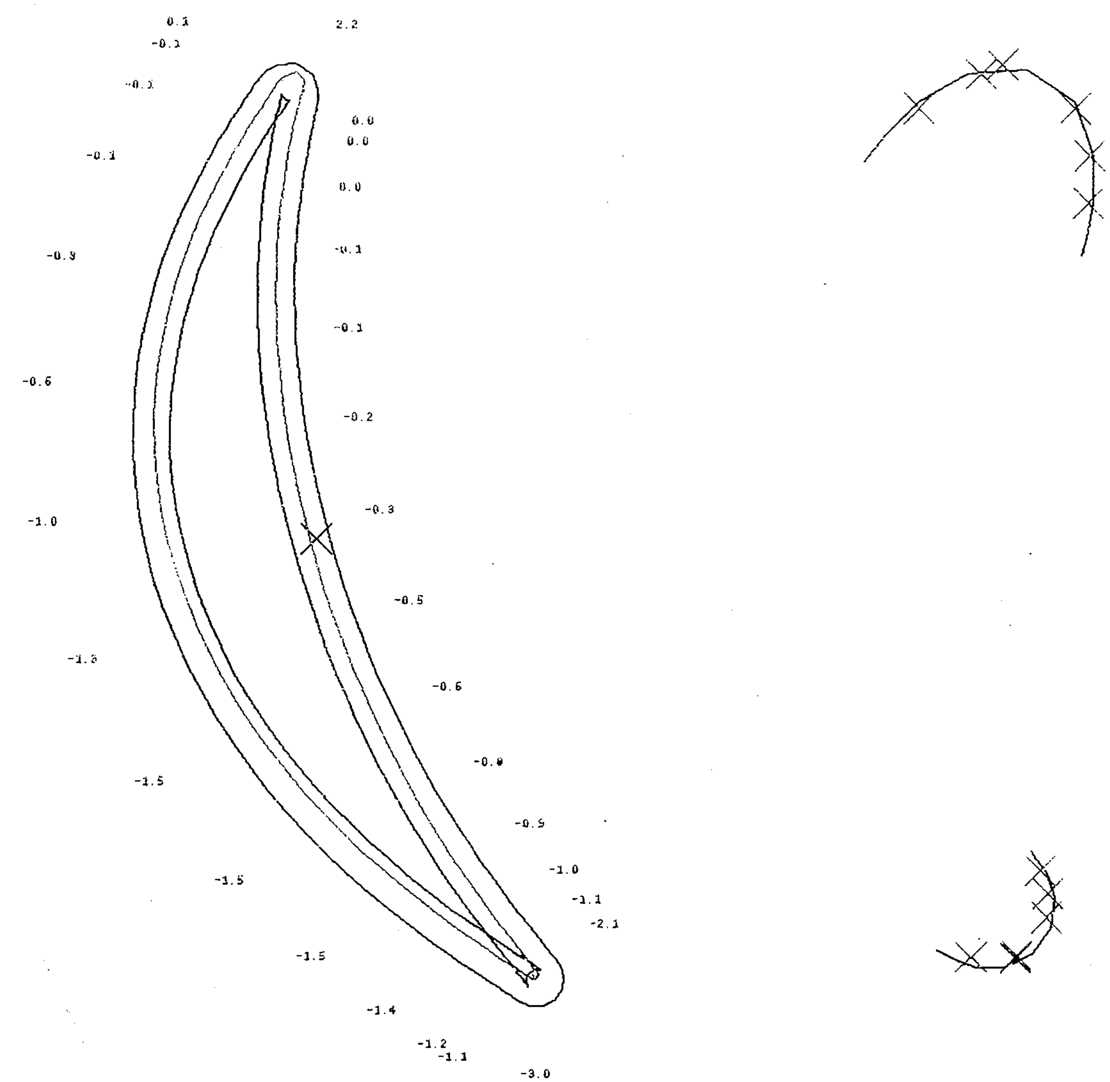
1.9

-2.3

0.179 Deg

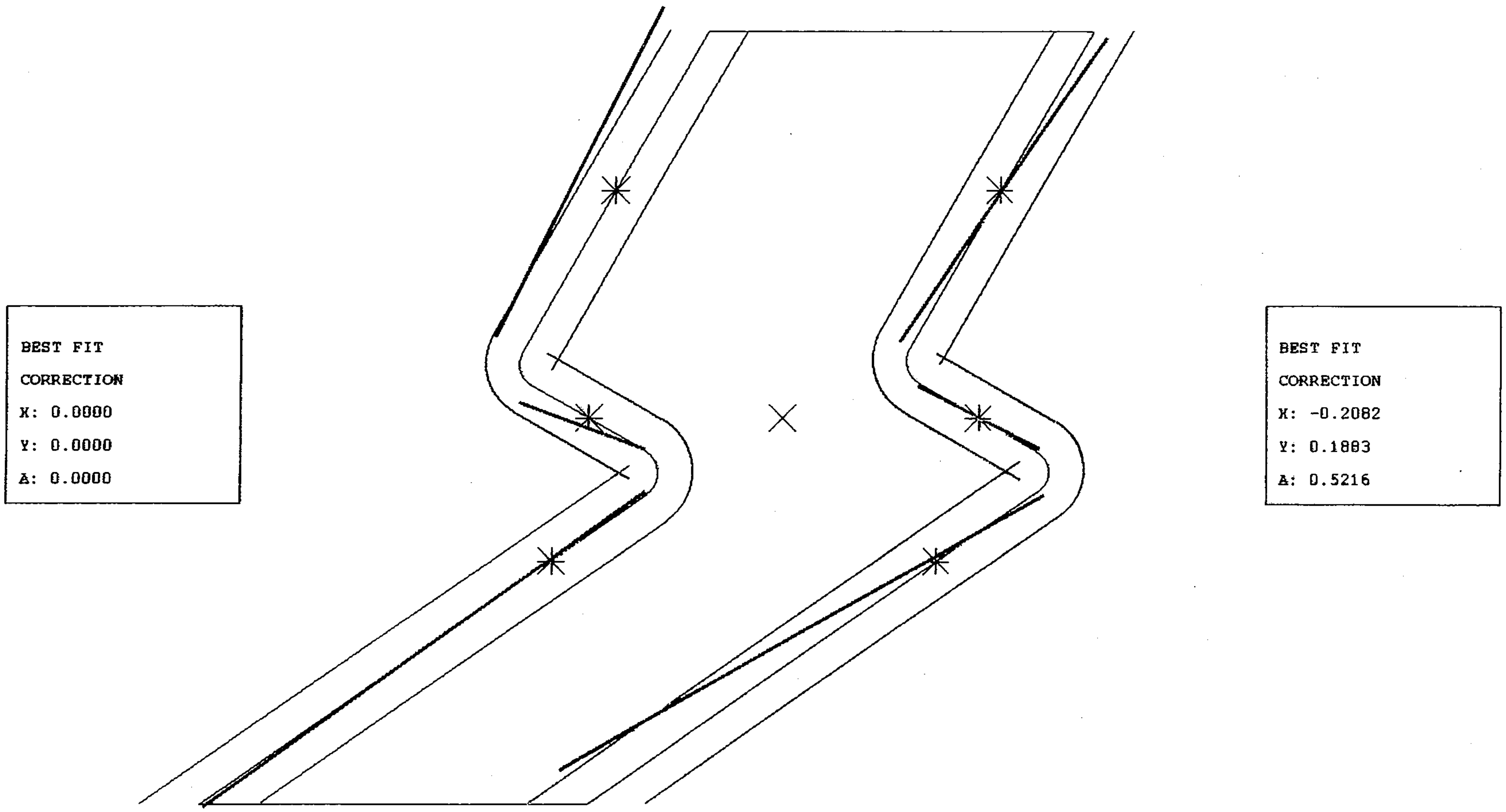
CHORD : -0.6

TE THK: -2.3



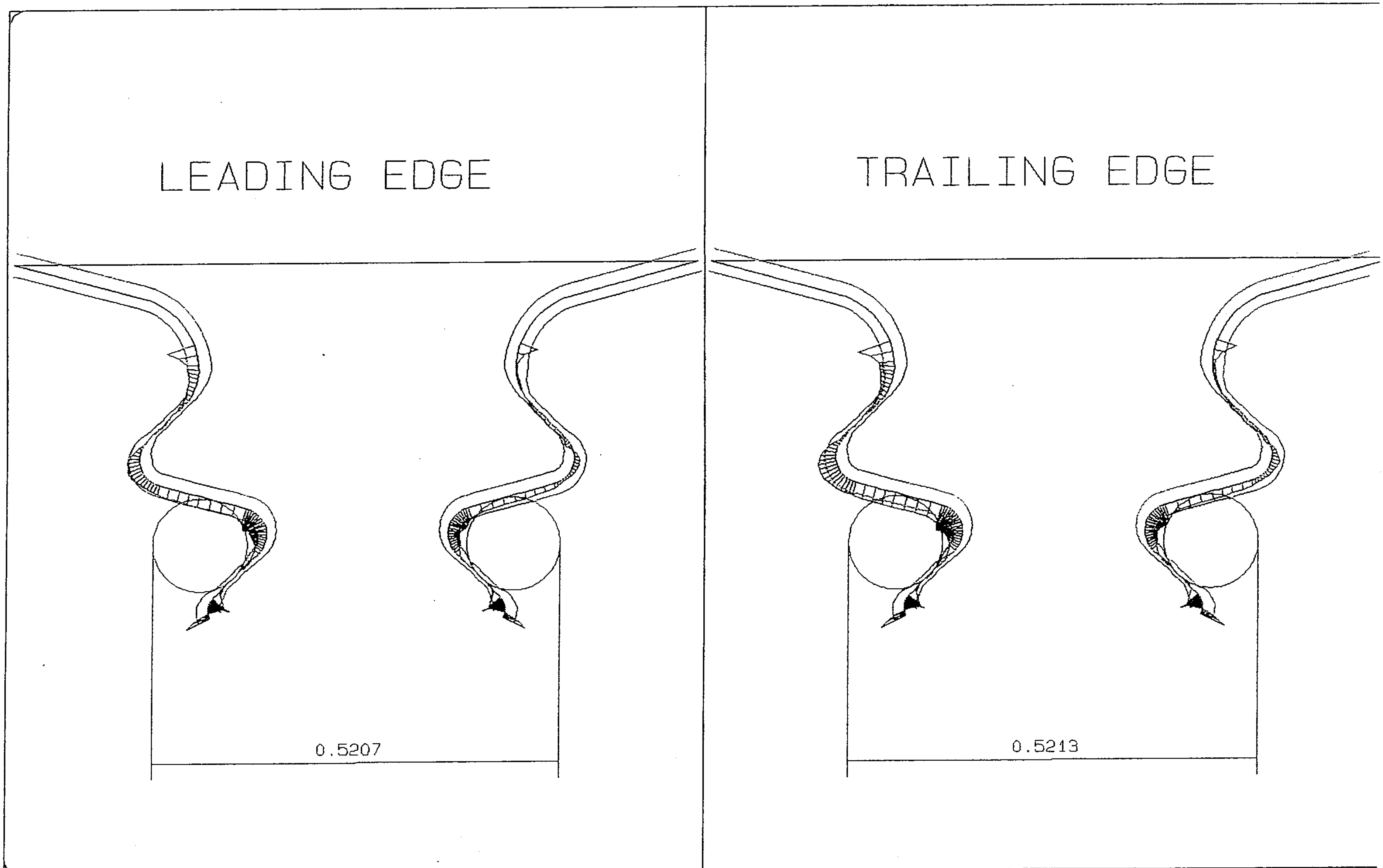
Right side corrected and XYR effect to left side displayed

Tolerance Bandwidth : 0.152 Error Magnification : 15



Click trackerball key to continue

Shroud alignment using three reference points.



Leitz QUINDOS

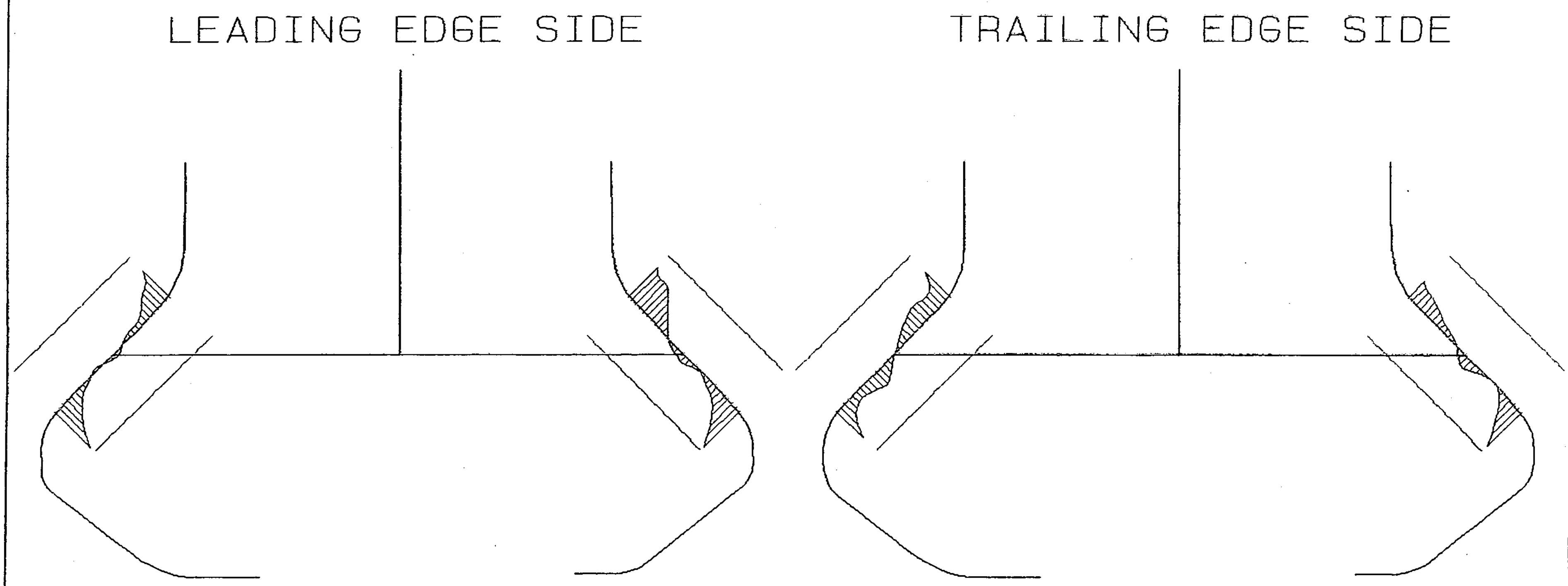
FIRTREE EVALUATION

TOLERANCE +/- 0.0005 TO +/- 0.0015

Inspector . PMM432
Date .....: 2-OCT-96
Time .....: 10: 56: 25

PLOT ILLUSTRATING THE 2 DOVETAIL SCANS

DEVIATIONS SHOWN AT A MAGNIFICATION OF x20

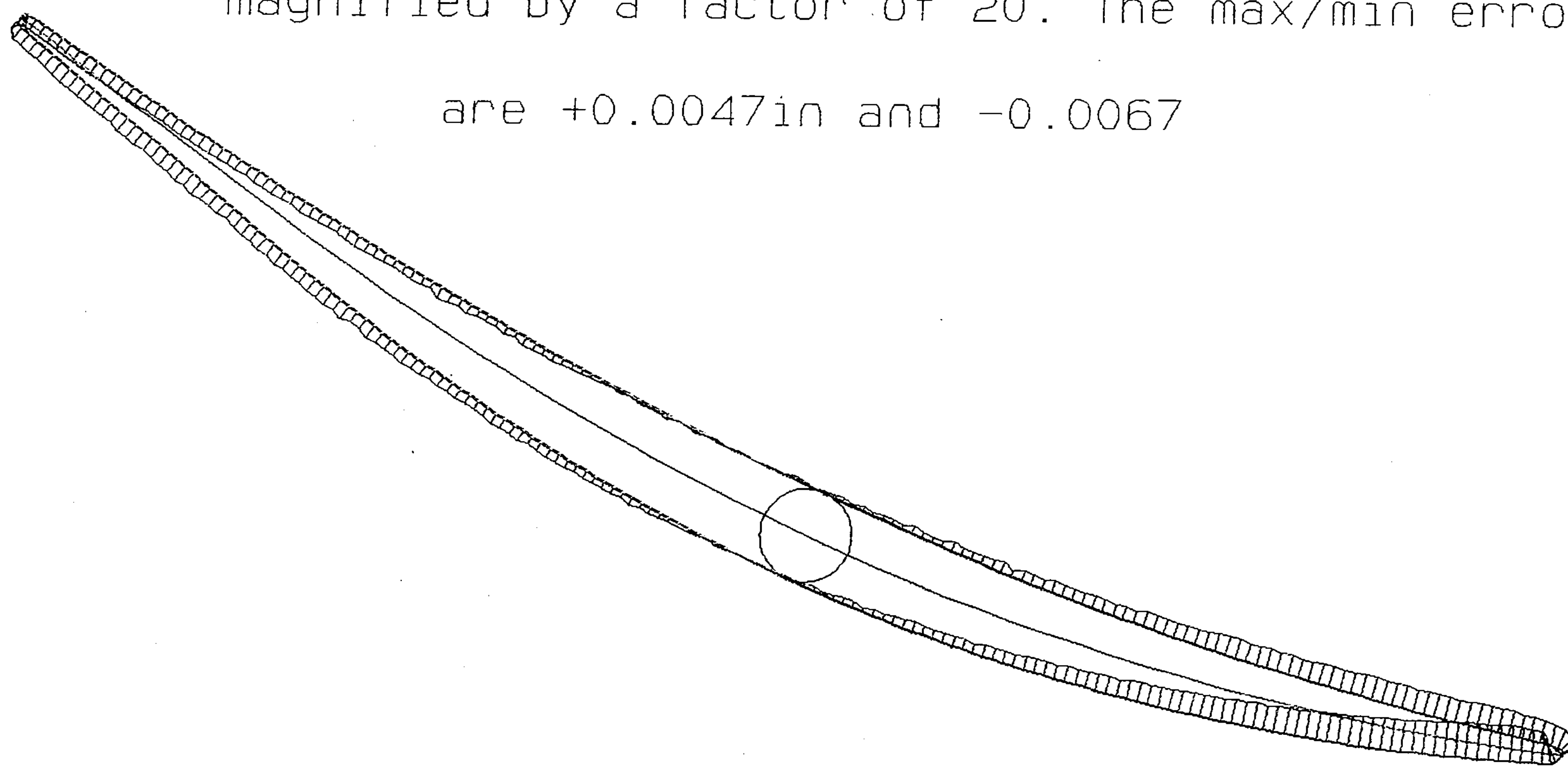


Blue illustrates the 3D radius corrected profile

Red illustrates the 2D profile compared to the 3D profile

magnified by a factor of 20. The max/min errors

are +0.0047in and -0.0067



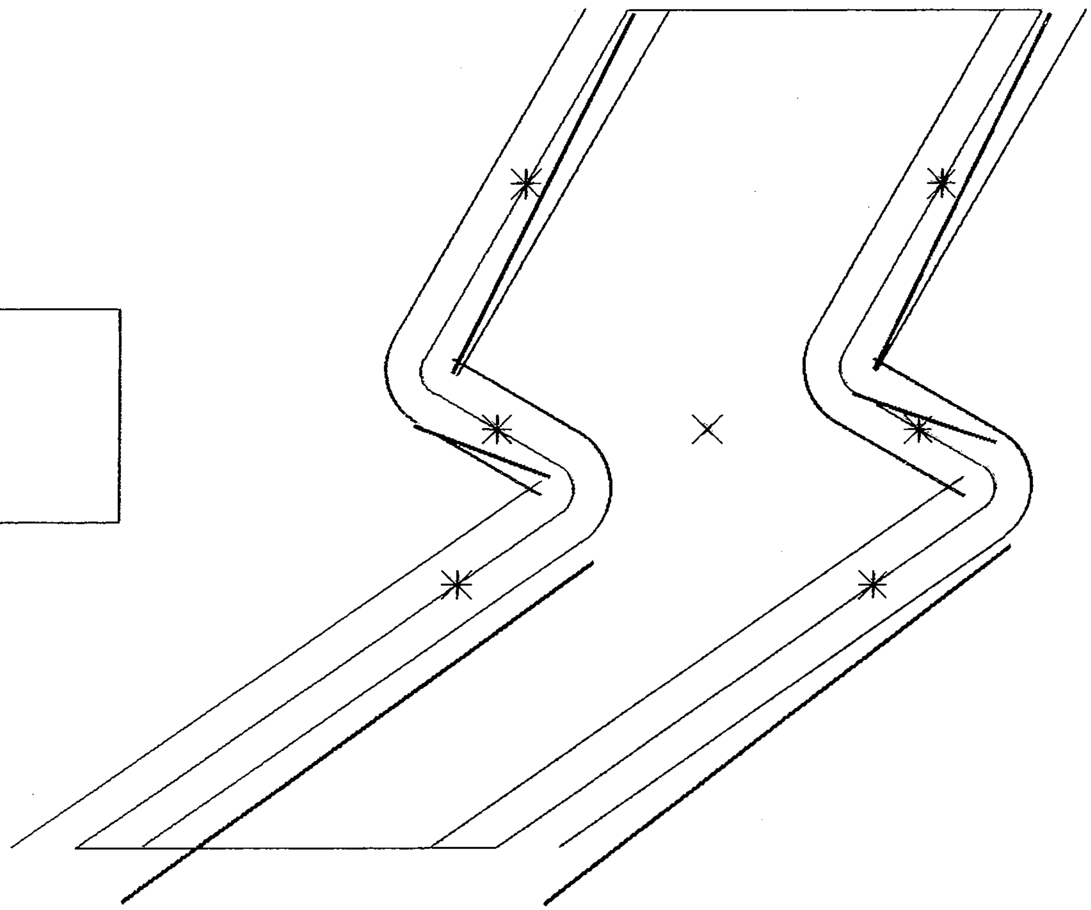
The green line and circle illustrate the mean camber line

and point of maximum thickness

Left and right displayed as measured

Tolerance Bandwidth : 0.152 Error Magnification : 15

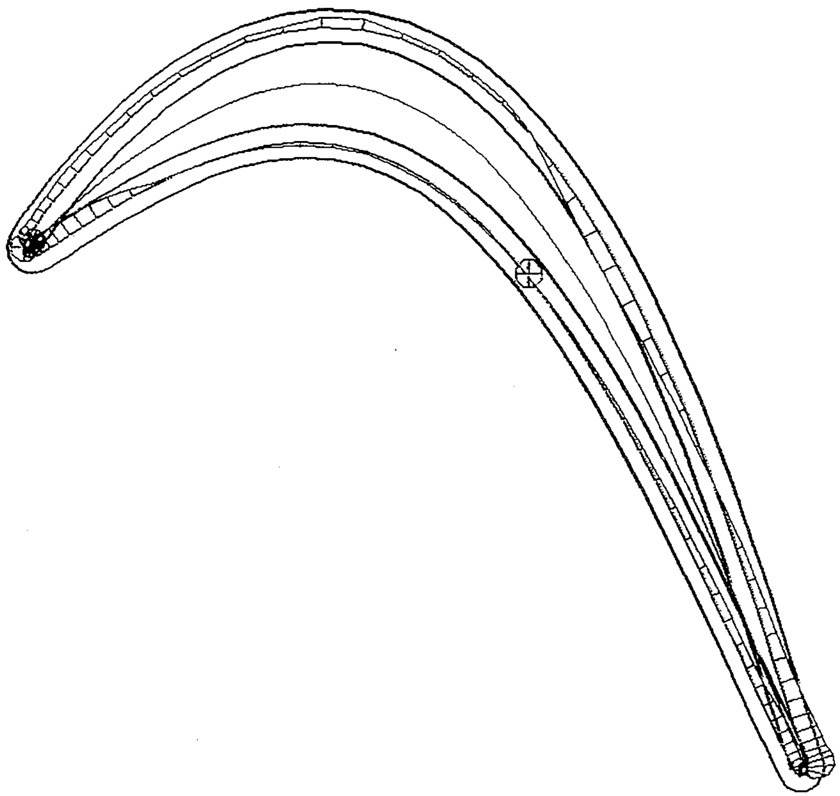
BEST FIT
CORRECTION
X: 0.0000
Y: 0.0000
A: 0.0000



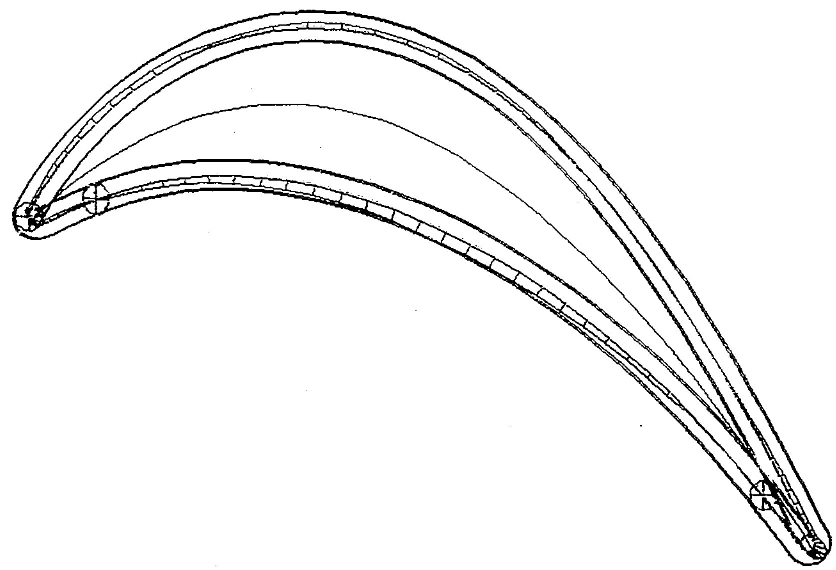
BEST FIT
CORRECTION
X: 0.0000
Y: 0.0000
A: 0.0000

Click trackerball key to continue

SECTION GG



SECTION AA

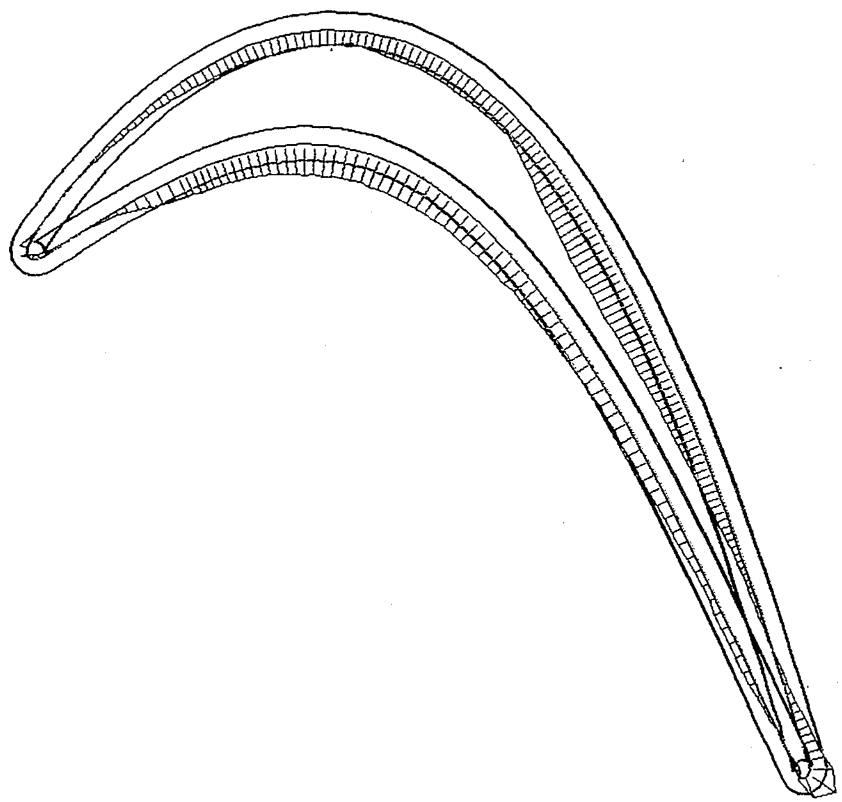


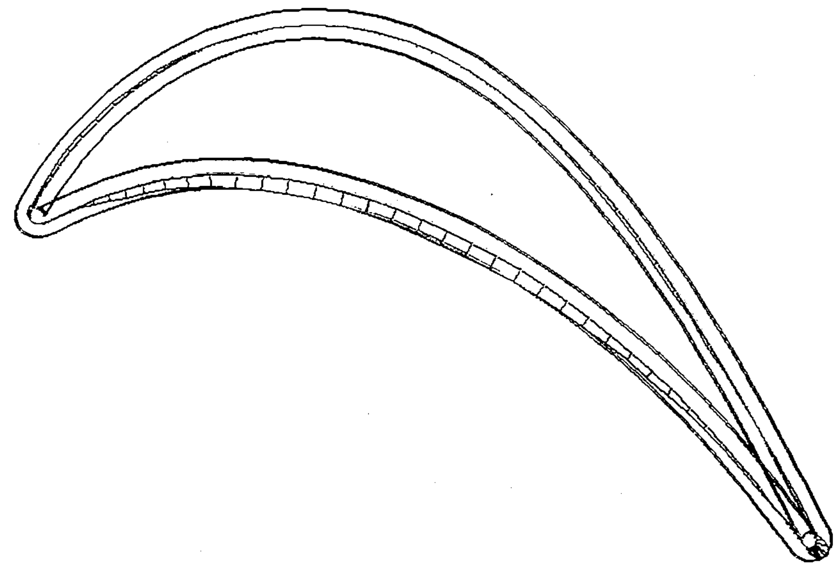
Leitz QUINDOS

AIRFOIL EVALUATION

RELATIVE TO CAST DATUM
TOLERANCE +/- 0.005
GREEN POINTS REPRESENT THE NOMINAL ALIGNMENT POINTS

Inspector . PMM432
Date .....: 2-OCT-96
Time .....: 10: 56: 25



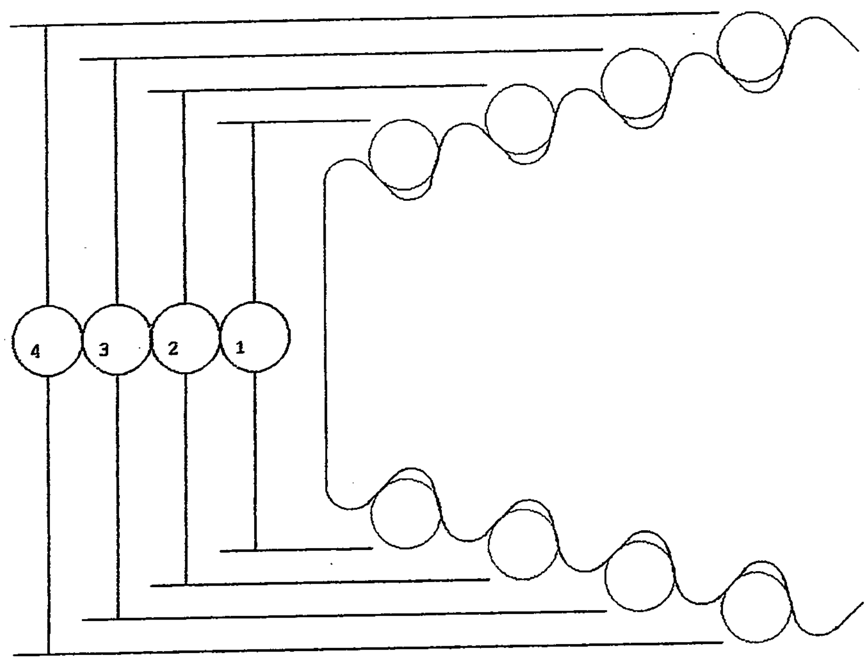


QUINDOS

AIRFOIL EVALUATION
BEST FITTED AT 5% AND 95% OF CHORD
TO MINIMISE NOSE DEVIATIONS
TOLERANCE +/- 0.005

Inspector . PMM432
Date .....: 2-OCT-96
Time .....: 10: 56: 25

PART # UL27515 UNITS: METRIC DATE/TIME: 14-Mar-94/14:19:54



PLOT OVER WIRES

PLOT PRESSURE FACES

PLOT OVER PEAKS

PLOT OVER VALLEYS

OUTPUT TO PRINTER

QUIT THIS SCREEN

No	NOM'L	ACTUAL	DEVN
1	10.589	11.355	0.766
2	12.255	13.020	0.766
3	13.912	14.678	0.766
4	15.570	16.335	0.766

Typical results for firtree inspection (MicroMeasure IV).

DATE/TIME : 03-Mar-94/14:10:54 — Part No : 353.DAT

Customer : KAWASAKI — Blade Condition: 1st_CNC

Result : FAIL

FEATURE	B-B ROOT	C-C	D-D MID	E-E	F-F	USL	LSL	CLASS
LE THK	0.0119					0.0140	0.0100	P
LE THK		0.0109	0.0109	0.0110	0.0110	0.0130	0.0090	PPPP
MAX THK	0.0120					0.0140	0.0100	P
MAX THK		0.0110	0.0110	0.0110	0.0110	0.0130	0.0090	PPPP
TE THK	0.0119					0.0140	0.0100	P
TE THK		0.0109	0.0109	0.0109	0.0109	0.0130	0.0090	PPPP
CHORD	-0.0102					0.0450	0.0350	U
CHORD		-0.0092	-0.0082	-0.0078	-0.0072	0.0450	0.0350	UUUU
C/C CONTOUR	0.0000	0.0000	0.0000	0.0000	0.0000	0.0030	-0.0030	PPPPP
LE INNER	0.0000	0.0000	0.0000	0.0000	0.0000	0.0030	-0.0030	PPPPP
MAX	0.0000	0.0000	0.0000	0.0000	0.0000	0.0030	-0.0030	PPPPP
TE INNER	0.0000	0.0000	0.0000	0.0000	0.0000	0.0030	-0.0030	PPPPP
C/V CONTOUR	0.0004	0.0003	0.0003	0.0003	0.0002	0.0030	-0.0030	PPPPP
LE INNER	0.0003	0.0002	0.0002	0.0002	0.0002	0.0030	-0.0030	PPPPP
MAX	0.0004	0.0003	0.0003	0.0003	0.0002	0.0030	-0.0030	PPPPP
TE INNER	0.0003	0.0002	0.0002	0.0002	0.0002	0.0030	-0.0030	PPPPP
TWIST (mins)	0.0					10.000	-10.000	P
TWIST (mins)		0.0	0.0	0.0	0.0	12.000	-12.000	PPPP
F DATUM	-0.0133					0.0020	-0.0020	U
F DATUM		-0.0109	-0.0088	-0.0074	-0.0058	0.0020	-0.0020	UUUU
S DATUM	0.0002					0.0020	-0.0020	P
S DATUM		0.0001	0.0001	0.0001	0.0001	0.0020	-0.0020	PPPP
DATUM ERROR	0.0133					0.0028	0.0000	R
DATUM ERROR		0.0109	0.0088	0.0074	0.0058	0.0028	0.0000	RRRR

PRINT RESULTS — NEXT PAGE — QUIT TO MENU

Typical results for compressor blade inspection (MicroMeasure IV).